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Spatial Yield Assessment of Sorghum (Sorghum Bicolor) Using DSSAT – CERES –Sorghum Model in Solapur, Maharashtra, India

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Authors' contributions

This work was carried out in collaboration among all authors. Authors HCR and KB carried out verification of output, and wrote the protocol and the first draft of the manuscript. Authors SP and NKSM generated the outputs. Authors NKSM and MP defined the methodology of the research and verification part. All authors read and approved the final manuscript.

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ABSTRACT

Accurate estimation of crop yield is crucial for ensuring food security and effective policy making. This study focuses on the estimation of sorghum yield in the Solapur region of Maharashtra (India), employing the Decision Support System for Agrotechnology Transfer (DSSAT) model. Sorghum is the fifth largely produced staple crop of the world which also plays a vital role in the food security produced by India. Maharashtra has the largest area under sorghum crop, and Solapur has the

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most area under rabi sorghum with an area of 4.6 lakh ha, accounting for 23% of the total area under rabi sorghum in the state. Although productivity is lower in Maharashtra than in other states, these studies will help us to get a preharvest estimate of the crop. Crop Cutting Experiments(CCE) were conducted for rabi sorghum and the model was validated for the simulated yields; which have a range of grain yield from 611 to 1525 kgs ha^{-1} and showed error with less than 14% and it was evaluated with statistical models such R^2, Nash-Sutcliffe efficiency (NSE) and Normalized Root Mean Square Error (NRMSE) and results show as 84%, 0.84 and 0.07. This model can be used further used for the yield gap analysis, and climate change studies for the locations.

Keywords: Sorghum; DSSAT; CERES; spatial yield; Solapur.

1. INTRODUCTION

Sorghum is one of India's most widely cultivated cereal crops, known for its ability to adapt to a variety of different agroclimatic conditions and for its versatility. Sorghum is mostly cultivated as a dryland cereal crop in India's Deccan Plateau, Central and Western India, with a few spots in Northern India. Since, its high mineral content, slow digestion, and high fibre content, it is nutritionally superior to other small grains like rice and wheat. Sorghum provides food and fodder security by reducing risk on a sustainable basis because it is typically grown in nutrient-poor soils in regularly drought-prone areas [1]. In addition to being economically valuable, it also has nutritive value, so it has become one of the most important ingredients in the agricultural landscape of our country. Sorghum plants are very hardy and can withstand high temperatures and drought. It is being successfully grown under atmospheric temperatures ranging between 15° C to 40° C and annual rainfall ranging from 400 to 1000 mm; It can be cultivated on a variety of soil types, but humus-rich clayey loam has been determined to be the best. However, healthy sorghum soil needs to have effective drainage because it can handle water logging better than maize. Its stover is important for animal feed and the grain for new value-added/processed food products such as popped sorghum, papad, porridge, rava and as an ingredient for umpteen Indian dishes like roti, dosa, khichdi, etc., a sign of its diverse utilization trends. Even though the crop is robust and versatile, it has faced drawbacks in terms of yield and reduction in acreage [2]. Sorghum harvested area is in the decreasing trend from 13.041 m ha to 4.093 m ha observed from 1991 to 2020 with a trend value of R^2=0.9788; As the fifth largest producer of sorghum globally (Fig. 1.), India plays a crucial role in meeting domestic consumption demands; from 1991 average yield data of sorghum is in non-significant increasing trend with highest productivity was observed in the year 2021, 2008 and 2020 [3].

In India, Maharashtra has the highest area and production followed by Karnataka, Tamil Nadu, Andhra Pradesh and Telangana (Fig. 2). In production wise Maharashtra and Karnataka stood top compared to Andhra Pradesh, Tamil Nadu and Telangana. But Andhra Pradesh and Telangana have the highest productivity this could be due to better irrigation facilities.

A timely, crop yield forecast has become essential to predict agricultural yield accurately well before harvest, especially in a nation like India where the weather is unpredictable.

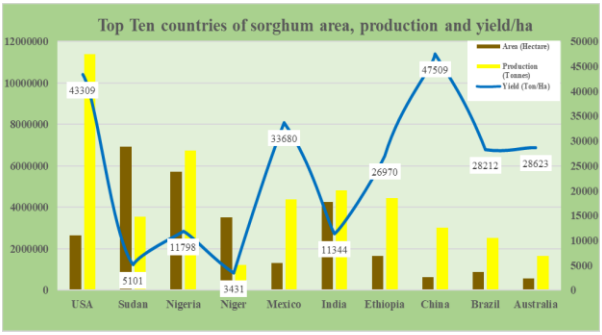

Fig. 1. Top 10 countries of sorghum area, production and yield/ha (2019-20)

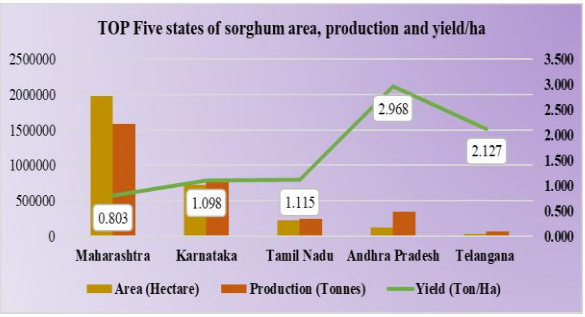

Fig. 2. Top five states of sorghum production in INDIA (2019-20)

Accurate crop forecasting may become a strategy for guaranteeing food security in the current scenario of changing climate, growing susceptibility, and food insecurity. For several user groups, such as agricultural planners and policymakers, crop insurance firms, and the research community, early yield assessment at regional and national sizes is becoming more crucial [4,5]. In order to make informed decisions that affect markets, export-import choices, and agricultural revenue planning, accurate and timely monitoring of possible yields is essential [6]. To integrate agronomic sciences with information sciences, the main instruments required are crop simulation models. Through the mathematical and conceptual link that controls a plant's growth in the continuum of soil, water, plant, and atmosphere, it is now possible to replicate a living plant using these crop models. The interactions between the environment and the crops are largely explained by crop simulation models [7]. For small stakeholders of farmlands with standing crops becomes an intricate decision led by the government and policymakers for proper pricing of different insurance premiums. The Pradhan Mantri Fasal Bima Yojana (PMFBY) program of the Government of India aims to enhance sustainable production in the agriculture sector by giving financial assistance, stabilizing farmers' incomes, and encouraging farmers to use new techniques. The scheme provides insurance to farmers in the event of crop losses. The Mahalanobis National Agricultural Forecast Centre (MNCFC) in New Delhi, India, assesses agricultural acreage, yield, and crop conditions across the country to assist insurance firms in determining crop premiums. MNCFC has financed pilot studies in India to assess rapidly and accurately yield estimations utilizing techniques such as remote sensing and crop simulation modelling as part of this project [8,9].

2. METHODOLOGY

2.1 Study Area

The district-level area estimates in Maharashtra, accounts for 81.5% of the production of Rabi sorghum in India. The Solapur district extends to an area of 14,89,500 ha and contributes 19% to states rabi sorghum production as of 2019-2020 (Fig. 3) which is located at 17.10 to 18.32° North, 74.42 to 76.15° East (Fig. 4) and this particular district accounts in the top two districts sown with the highest areas for rabi sorghum crop in its respective states. The experimental study was carried out in different locations in the Solapur district around 35 ground truth points (Fig. 6) along Crop Cutting Experiments (CCE) data were collected at random locations of experimental study and used for validation of the CERES model.

2.2 Minimum Datasets

2.2.1 Input data

Data was downloaded from NASA POWER (Prediction of Worldwide Energy Resource) for the duration of the Rabi season from 2nd fortnight of October, 2022 to 1st Fortnight of February, 2023 [10,11]. By weatherman a program in the DSSAT software is used to make the weather file and 35 files were made for the point-specific location and their graph maps are in (Fig. 5.); which were considered as the monitoring sites in which the date of sowing was set from 5-28th of October as of data collected during ground truthing and the soil files were gathered from the International Research Institute for Climate Society, Michigan State, University Harvest Choice, International Food Policy Research Institute at 1:10,000 scale with a 5-min resolution. These files were the inputs to

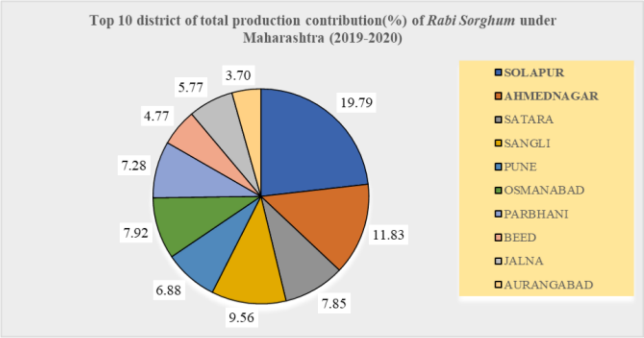

Fig. 3. Maharashtra top ten districts with most rabi sorghum crop Area

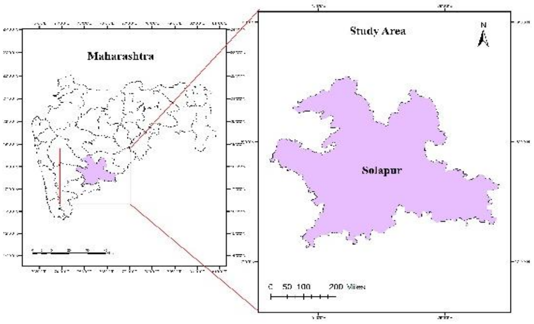

Fig. 4. Study area location Solapur (Maharashtra)

the model for the monitoring fields for the study area to be simulated. The crop management data of the file given was the rainfed crop.

2.2.2 Weather files of DSSAT

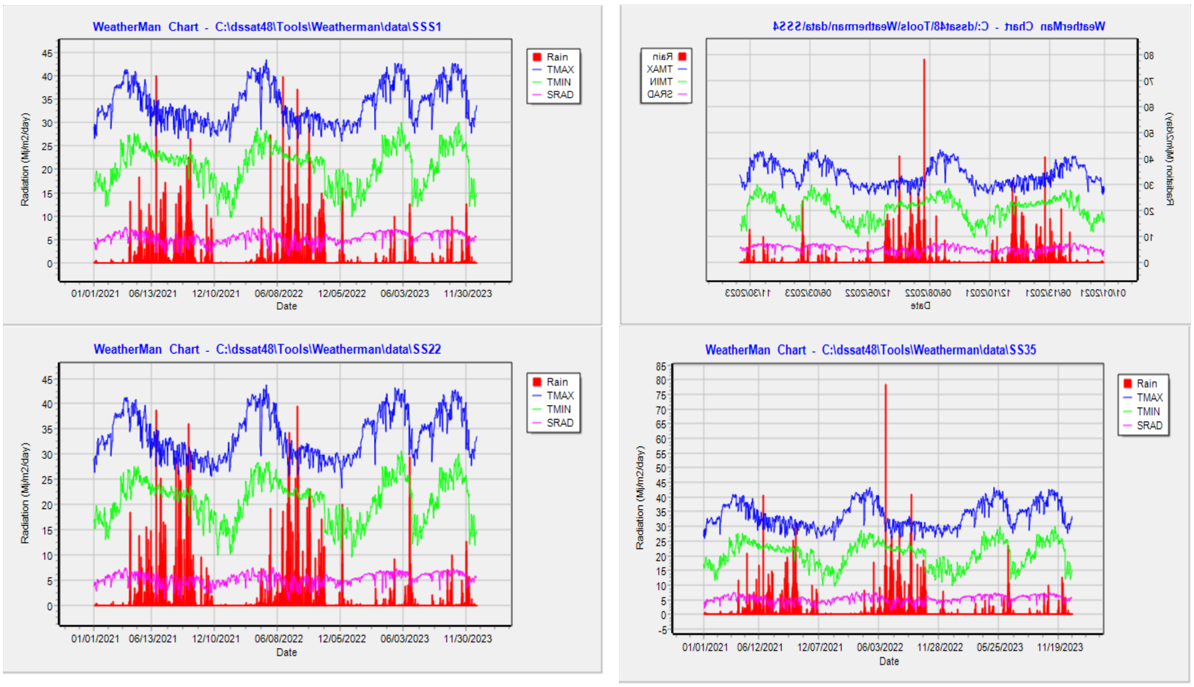

Fig. 5. Weather file for Solapur (Maharashtra)

2.3 Statistical Approach of Model Evaluation

The model's performances were evaluated using statistical indices including the coefficient of determination (R^2), Nash Sutcliffe model Efficiency coefficient, and % Error to evaluate the model's goodness of fit and performance [12].

2.3.1 Pearson's correlation coefficient (r) and coefficient of determination (R^2)

$R^2 = 1 – (RSS/TSS)$
R^2 = Coefficient of determination
RSS = Sum of squares of residuals
TSS = Total sum of squares

2.3.2 Nash Sutcliffe model efficiency coefficient

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance [13]. Nash-Sutcliffe efficiency indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE = 1, corresponds to a perfect match of the model to the observed data. NSE = 0, indicates that the model predictions are as accurate as the mean of the observed data, and Infinite < NSE < 0, indicates that the observed mean is a better predictor than the model.

where OBSi is the observation value and SIM_i is the forecast value and OBS bar is average of observation values.

$$\text{NSE}=\frac{\sum_{i=1}^{n}(OBSi-SIMi)^2}{\sum_{i=1}^{n}(OBSi-\overline{OBS})^2}$$

2.3.3 NRMSE (Normalized Root Mean Square Error)

The Normalized Root Mean Square Error (NRMSE) the RMSE facilitates the comparison between models with different scales. the normalized RMSE (NRMSE) which relates the RMSE to the observed range of the variable. Thus, the NRMSE can be interpreted as a fraction of the overall range that is typically resolved by the model.

$$\text{NRMSE}=\frac{RMSE}{\overline{O}}$$

where O_{bar} is the average of observation value and you can find the formula of RMSE by click on it.

2.3.4 % Error (Deviation) is calculated

The values of the % error for each point location is given in the Table 2.

$$\textbf{\%Error}=\frac{simulated-observed}{observed}*100$$

2.4 CERES-sorghum Genetic Coefficients

The calibration of the CERES – Sorghum module of the Decision Support system for Agrotechnology transfer (DSSAT), data on plant growth and development, soil characteristics, weather, and crop management were collected as required for determining the cultivar coefficients of as prescribed in the following the procedures described in International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). These coefficients allow the model to simulate the performance of diverse genotypes under different soil, weather and management conditions. To determine the genetic coefficients of Sorghum, the calibrated values are obtained by permutating and computing the values to determine the variation in the magnitude of output manually. Then, those values of the genetic coefficients that was found most realistically simulated the growth and yield of *rabi* sorghum were selected. The data set for genetic coefficients calculations include days to anthesis, days to first pod, days to physiological maturity, days to harvest maturity, seed yield, by-product leaf area and harvest index. The procedure for determining genetic coefficients involved in running the model using a range of values of each coefficient, until the desired level of agreement between simulated and observed values was reached.

3. RESULTS AND DISCUSSION

3.1 Genetic Co-efficient of Sorghum for CERES Sorghum Model

The field experimental data collected during 2020-21 and 2021-22 during the Rabi season for three sorghum varieties namely Maldandi (M-35-1), Mauli and Yashoda and the genetic coefficients of varieties present in the InfocropV2.01 model [7] were used. The details of the coefficients derived and converted into DSSAT genetic coefficients in which Maldandi (M35-1) has already existed then Mauli and Yashodha were derived from the permutation and computation [14]. In (Table 1) calibrated CERES Sorghum module with data on plant growth and development, soil characteristics, weather, and crop management were collected as required for determining the cultivar coefficients were given in the table.

3.2 Yield Analysis

The observed yield and simulated yield are compared, and their Standard error is calculated. Among the 35 locations yield data were validated. For all the varieties in the given district were simulated well with the simulated yield with locations taken under the map in (Fig. 6.) and (Table 2) of yield.

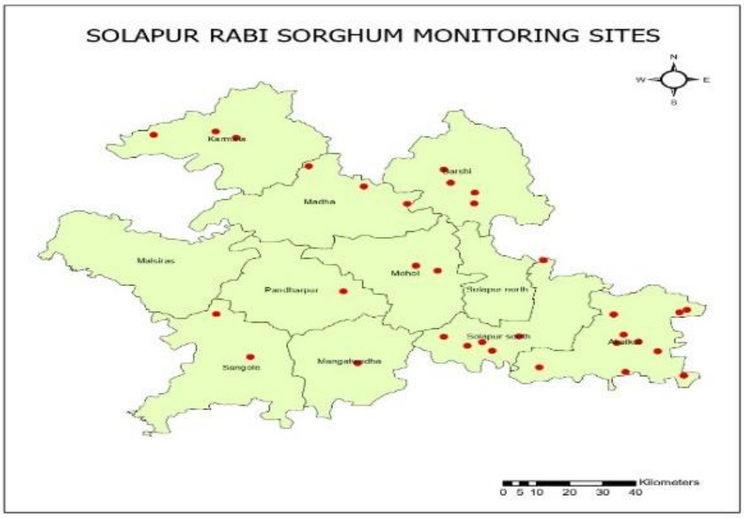

Fig. 6. Solapur monitoring sites

Table 1. Calibrated genotypic coefficients for rabi sorghum cultivar

Coefficient code	Description	Genetic coefficient		
		Maldandi (M35)	**Mauli**	**Yashodha**
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above TBASE during which the plant is not responsive to changes in photoperiod	320	300.1	282.1
P2	Thermal time from the end of the juvenile stage to tassel initiation under short days (degree days above TBASE)	102	102	102
P2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P2O, the rate of development is reduced	14	12.46	12.46
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O	45.6	111.1	123.1
PANTH	Thermal time from the end of tassel initiation to anthesis (degree days above TBASE)	617.5	617.5	617.5
P3	Thermal time from to end of flag leaf expansion to anthesis (degree days above TBASE)	152.5	152.5	152.5
P4	Thermal time from anthesis to beginning grain filling (degree days above TBASE)	81.5	81	81
P5	Thermal time from beginning of grain filling to physiological maturity (degree days above TBASE)	590	450	525
PHINT	Phylochron interval; the interval in thermal time between successive leaf tip appearances (degree days)	49	54.02	54.02
G1	Scaler for relative leaf size	15	7.2	7.2
G2	Scaler for partitioning of assimilates to the panicle (head).	4.5	5.6	5.6

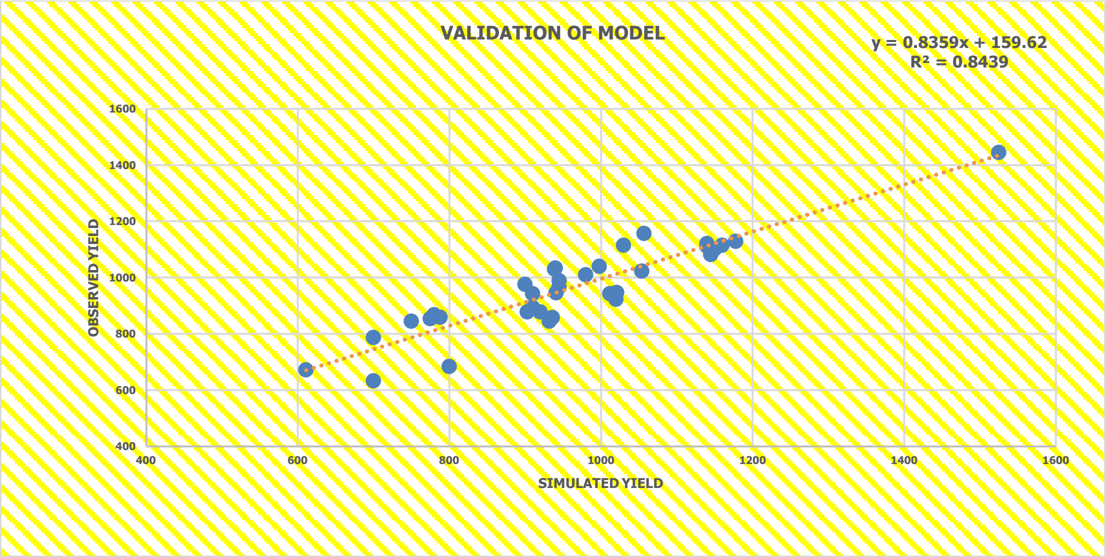

Fig. 7. Simulated and observed yield for validation

3.3 Validation of Model

The observed yield of sorghum was matched well after calibration which showed that model could simulate the yield with high accuracy, as it showed R2, Nash-Sutcliffe efficiency (NSE) and Normalized Root Mean Square Error (NRMSE) is as 84%, 0.84 and 0.07 this indicates a good efficiency [6] also observed the that the simulated biomass yield was slightly higher than that of the observed biomass yield in rice while using the DSSAT model. R2 values show a good significant value for the graph of observed and simulated yield values. The R2 values are good and significant, the 1:1 line graph was drawn showing observed yield in X-axis and simulated yield in Y-axis. The regression line of grain yield was near to the 1:1 line, indicating that the model was performing well under the test environment, thus model simulated the yield perfectly (Fig. 7).

Table 2. Observed and simulated yield for Solapur monitoring sites

Latitude	Longitude	Obs. Yield (Ha)	DSSAT sim. Yield (Ha)	% error
Variety- M35				
17.49481	75.82144	1020	923	-9.5
17.51930	75.92020	945	989	4.7
18.14387	75.73508	1054	1023	-2.9
17.49609	76.24502	1085	1121	3.3
17.70210	75.44345	1140	1112	-2.5
18.05813	75.61789	998	1040	4.2
17.82788	75.98696	1525	1445	-5.2
17.45936	75.84884	1030	1115	8.3
17.51730	75.71688	1160	1115	-3.9
17.60783	76.17765	1150	1101	-4.3
17.45923	76.29715	1178	1129	-4.2
17.80615	75.64110	1145	1082	-5.5
18.21058	75.35038	980	1010	3.1
18.32605	75.15290	1057	1157	9.5
17.40990	75.48366	940	1034	10.0
Latitude	**Longitude**	**Obs. Yield (Ha)**	**DSSAT sim. Yield (Ha)**	**% error**
Variety- Mauli				
17.52420	76.20540	1012	943	-6.8
18.35189	75.09761	910	894	-1.8
17.37428	76.20953	1021	947	-7.2
17.62613	76.37560	903	878	-2.8
17.61536	76.35649	920	878	-4.6
17.49202	76.18707	800	684	-14.5
18.33834	74.92818	900	976	8.4
17.60783	76.17765	910	943	3.6
Latitude	**Longitude**	**Obs. Yield (Ha)**	**DSSAT sim. Yield (Ha)**	**% error**
Yashodha				
18.06008	75.79819	780	868	11.3
18.10370	75.80110	775	854	10.2
17.80615	75.64109	750	845	12.7
17.43568	75.19119	939	1030	9.7
18.19766	75.71659	936	858	-8.3
18.14387	75.73508	788	859	9.0
17.45923	76.297146	700	633	-9.6
17.39322	75.97563	941	946	0.5
17.78650	75.69935	932	845	-9.3
17.35854	76.36807	945	966	2.2
17.60904	75.09834	700	787	12.4
18.12800	75.49930	611	672	10.0

R2 value 84% for grain yield of Rabi sorghum was observed and similar coefficient of correlation value was observed after validation of CERES -CROPGRO module at Vidisha and Nagaur for chickpea [15]. A model showed “fair” to “good” in grain yield prediction by comparing the observed yields as of the [16,17] has observed similar evaluation results of the model in spring maize in northeast China showed almost similar evaluation figures in normalized root mean squared error (nRMSE), Nash-Sutcliffe efficiency (NSE).

4. CONCLUSION

The simulated yield of the DSSAT CERES Sorghum module revealed that simulated the yield were very closer to observed crop yield and it has proved to be a valuable tool for predicting sorghum yield. Therefore, the validated DSSAT can be further used for applications such as prediction of crop growth, phenology, potential and actual yield, climate change impacts, adaptation and vulnerability studies, yield gap analysis etc., The model can also be used to evaluate and improve the current practices of sorghum to increase the yield. CERES module can be used to simulate crop growth and its development as well as THE prediction of yield spatially for different conditions of soil, weather and management practices to enhance Sorghum production. It could be concluded that the model works well for in rainfed growing environments and further, it can be taken for application in natural resource management and climate change impact analysis studies.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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